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Estimation of HDR WCG Display Color Gamut Volume

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Abstract

Triangular gamut area plots on chromaticity diagrams (e.g., CIE xy or CIE u'v') have long been used in attempts to describe and compare the range of colors that can be produced on displays. This has been done despite the long-established recognition that three-dimensional color gamut volumes in color appearance spaces (e.g. CIELAB or CIECAM02) more appropriately describe display performance. Since three-dimensional color gamut volumes are often difficult to measure and compute, this paper suggests a simple model to estimate color gamut volumes from chromaticity gamut areas, CLO/WLO ratio, peak luminance, and diffuse white luminance for RGB and RGBW wide-color-gamut and high-dynamic-range displays.

Introduction

The visualization, comparison, and analysis of display color gamut has a long history in the science of image reproduction. Traditionally, and even to date in many analyses, gamuts are visualized and compared in chromaticity diagrams, usually the CIE *xy* diagram, but sometimes in the CIE *u'v'* chromaticity diagram which has the potential to more uniformly represent the perceptions of hue and saturation. It should be clearly noted that such 2D gamuts cannot properly be called color gamuts since they neglect the basic properties of color appearance as well as the all-important dimensions of lightness and brightness. Examination of color gamuts requires the use of at least 3D color appearance spaces such as CIELAB or CIECAM02. In such spaces, color gamut volumes, a more meaningful metric of display color performance, can be computed [1]. The purpose of this paper is to computationally analyze the relationship between simple gamut metrics and full 3D color gamut volumes to determine whether a simplified set of measurements and computations can be used to estimate gamut volume.

While fundamental color science suggests that CIE *u'v'* chromaticity gamut areas might be more meaningful for comparisons of display appearance properties, Masaoka and Nishida [2] have illustrated an interesting properties of chromaticity gamuts. They showed that the CIE *xy* chromaticity gamut area is very highly correlated with 3D color gamut volume expressed in any of the CIE appearance spaces, including CIELAB, CIELUV, and CIECAM02. The CIE *u'v'* chromaticity gamut area, on the other hand showed no significant correlation with color gamut volume in any color space. Thus, CIE *xy* chromaticity gamut area can be used as a proxy for 3D color gamut volume for simple RGB displays [2]. That work is utilized as part of the model for prediction of color gamut volumes derived in this paper. Later, Masaoka[3] further analyzed the causes of these correlations and showed that it was due to the relative weighting of various chromaticity regions with respect to the display gamut volume in those regions.

Masaoka [4] followed up that work by illustrating the importance of 3D color gamut volume in CIELAB for the comparison of HDR-WCG displays. In particularly this is critical when comparing RGB displays with RGBW displays or when comparing displays with disparate peak luminance levels or ratios between peak luminance and rendered diffuse white luminance. This work also illustrated a strong correlation between color gamut volume and peak luminance and CLO/WLO ratio [4]. CLO is the Color Light Output defined as the sum of the full-on luminances of the three (RGB) display primaries. WLO is the White Light Output defined as the maximum luminance of the display. The two can differ if a display incorporates a white primary (RGBW), or if the display algorithm manipulates the power output for certain colors. These relationships are further explored and exploited in the model derived in this paper.

An alternative approach to visualizing and comparing 3D color gamut volumes in 2D plots was recently published [5]. That work converts gamut volume into "rings" of gamut areas as a function of relative luminance represented at the appropriate hue angle. While that work helps significantly in visualizing color gamut volumes it does not provide a simplification to the computation process or simple summary metrics that can be easily used in the display industry. The purpose of the present research is to do just that.

This paper examines 3D color gamut volumes in CIELAB and CIECAM02 JCh for a variety of simulated RGB and RGBW displays with different assumptions about peak luminance, diffuse white luminance, and surround relative luminance. Some of the viewing conditions selected were derived from the recommendations for HDR television in ITU-R BT.2100-1 [6]. Using the computed gamut volumes a model was derived to predict color gamut volume from chromaticity gamut area (*xy*), CLO/WLO ratio, and peak luminance. This model was then evaluated in a second simulation using independent display parameters.

Analysis and Modeling

For initial analysis of HDR and WCG display gamuts, the following parameters were evaluated to create a range of results. Peak luminances of 500, 1000, 2000, and 4000 cd/m^2 (nits) were evaluated. Primary sets were selected to be those of Rec.709, DCI P3, and Rec. 2020. Both RGB displays and RGBW displays with CLO/WLO ratios of 0.1, 0.3, 0.5, 0.7, and 0.9 were considered. (RGB displays have a CLO/WLO ratio of 1.0.) Color gamuts were evaluated in both CIELAB and CIECAM02 JCh color spaces. Limited experiments indicate that CIELAB remains approximately perceptually uniform above diffuse white up to L^* of at least 200 [7,8]. Computations were completed using diffuse white luminance of 200 cd/m^2 regardless of peak luminance and for diffuse white luminance equal to 20% of the peak luminance. For the extended CIELAB color appearance space, the same equations are used for tristimulus values greater than those of the D65 reference white at a luminance of 200 cd/m^2 ($L^* = 100.0$) based on the ITU-R Report for operational practices in HDR television production [9]. Due to limited space in this paper, only examples of typical results and the summary models are presented.

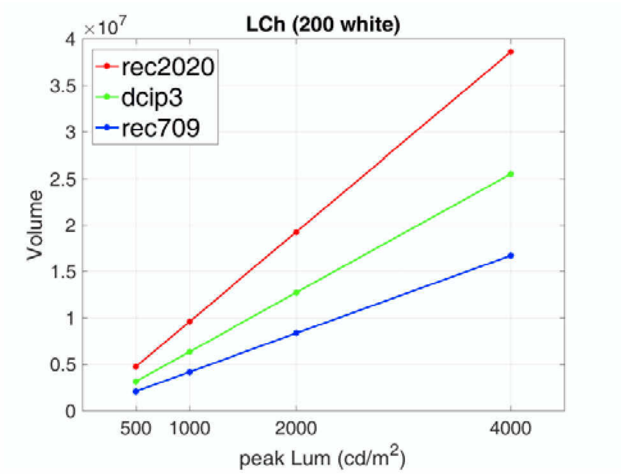


Figure 1. CIELAB gamut volume as a function of peak luminance for a 200cd/m² diffuse white and three standard primary sets.

Figure 1 shows CIELAB color gamut volume for three sets of primaries as a function of peak luminance with the diffuse white set at 200 cd/m². Gamut volume grows substantially and essentially linearly with peak luminance due to the fixed white point luminance since the gamuts are growing well beyond the range of surface color appearance to incorporate light sources and other extraspectral appearances. These results suggest a simple relationship between color gamut volume and peak luminance for any given set of primaries. Figure 2 shows similar results for CIECAM02 JCh color gamut volume. Again, there is a rather simple relationship between gamut volume and peak luminance for any given set of primaries.

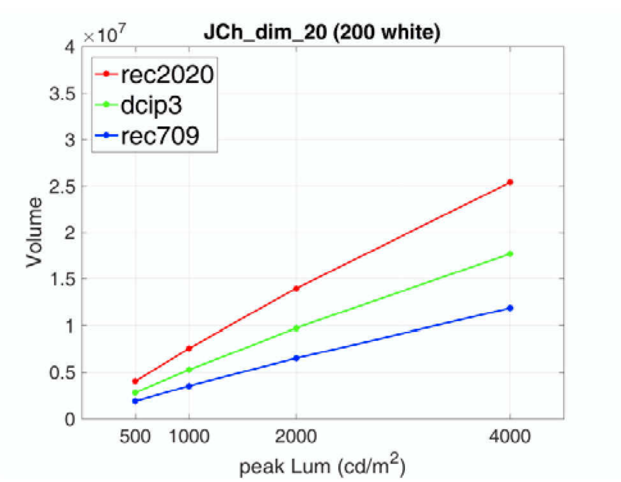


Figure 2. CIECAM02 JCh gamut volume as a function of peak luminance for a 200 cd/m² diffuse white, L_a = 20% of diffuse white, dim surround, and three standard primary sets.

On the other hand, Figure 3 illustrates the color gamut volume in CIELAB as a function of peak luminance when the diffuse white is taken to be 20% of the peak white. As expected, the gamut volumes depend on primary set, but they do not depend on peak luminance. This is because CIELAB is a relative color appearance space that is independent of the peak luminance so long as the diffuse white is taken as a constant percentage of the peak. In such cases, peak luminance becomes irrelevant to the prediction of color gamut volume (likely not a desirable outcome). Figure 4 shows similar results in CIECAM02 JCh (which is also a relative space for lightness and chroma, CIECAM02 QMh, predicting brightness and colorfulness, would behave differently.). All CIECAM02 results are shown for a dim surround. Similar trends are seen for computations with other surrounds and adapting luminance levels.

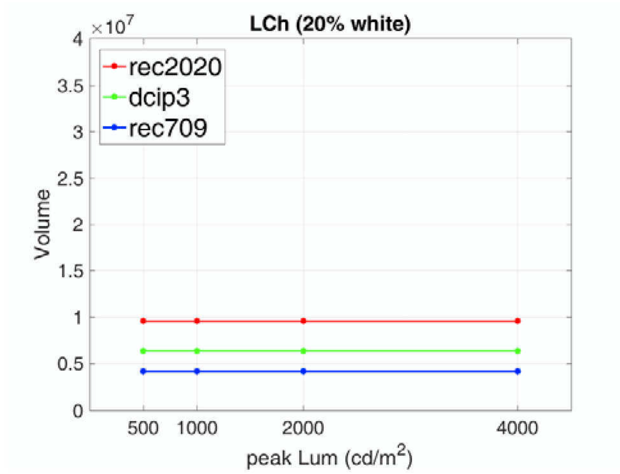


Figure 3. CIELAB gamut volume as a function of peak luminance for a diffuse white of 20% of peak white and three standard primary sets.

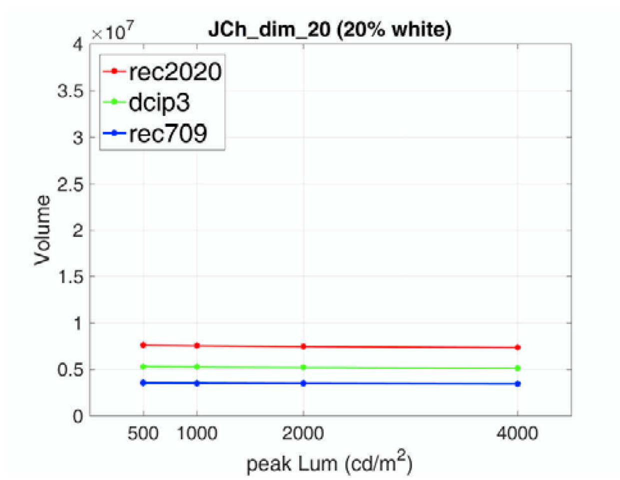


Figure 4. CIECAM02 JCh gamut volume as a function of peak luminance for a diffuse white of 20% of peak white, L_a of 20% diffuse white, dim surround, and three standard primary sets.

Figure 5 illustrates the relationship between the normalized color gamut volume, normalized to the volume for an RGB display (CLO/WLO = 1.0) with the same primaries, as a function of CLO/WLO ratio for the CIELAB LCh color space. Note that the relationship is similar for all three primary sets and can be replicated with a 4th-order polynomial (simply a description of the data, not a physical model) within the domain of the data. Figure 6 illustrates similar results for the CIECAM02 color gamut volume. Thus, color gamut volume can be related to both peak luminance and CLO/WLO ratio for any given set of primaries. What remains is to explore the definition of the primaries and their effects on color gamut volume.

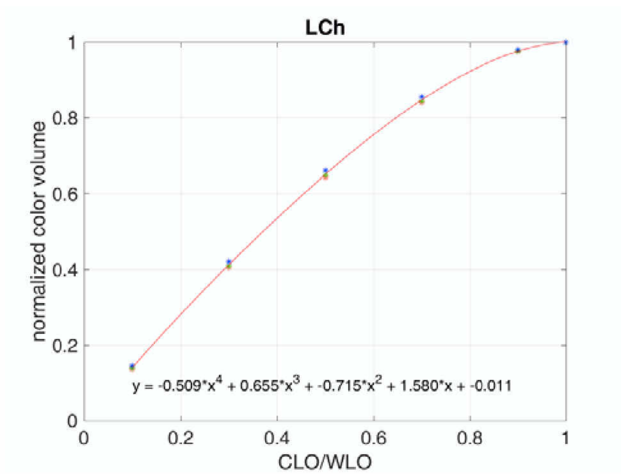


Figure 5. Relationship between CIELAB normalized color gamut volume and CLO/WLO ratio for a variety of displays.

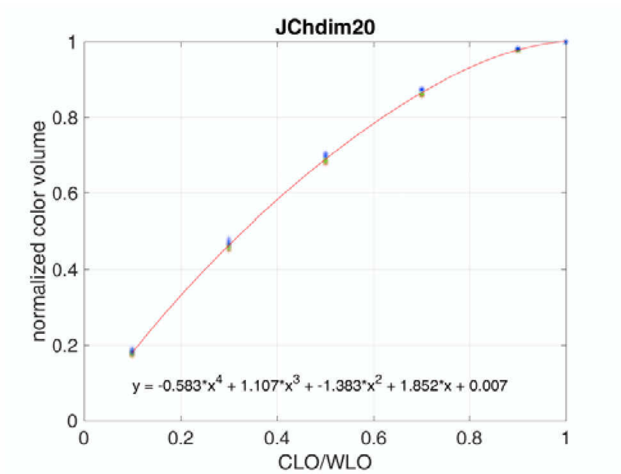


Figure 6. Relationship between CIECAM02 JCh normalized color gamut volume (dim surround) and CLO/WLO ratio for a variety of displays.

To examine the correlation and linearity between color gamut volume and CIE *xy* area coverage as proposed by Masaoka [2, 3], hundreds of virtual RGB primary sets were simulated and gamuts were calculated. Primaries were selected by creating a grid of data in the chromaticity areas between Rec. 2020 and Rec. 709 as illustrated in Figure 7. 1317 virtual primary sets in total were created and analyzed. In this case, the simulated peak luminance was 4000 cd/m^2 and diffuse white was equal to 800 cd/m^2 with RGB displays.

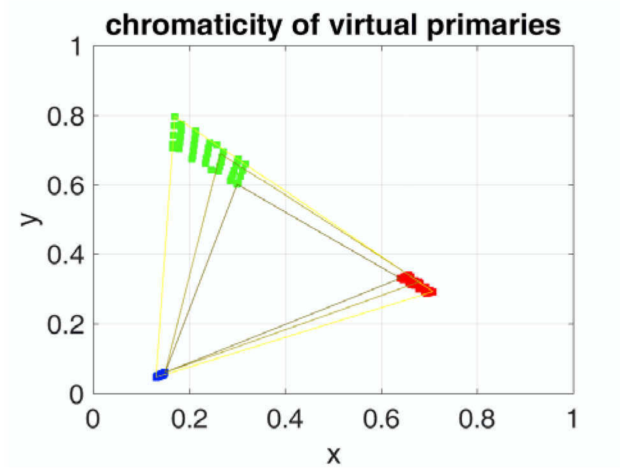


Figure 7. Primary chromaticities, along with Rec. 709, Rec. 2020, and DCI P3 gamut boundaries, used to create virtual displays for simulation and modeling.

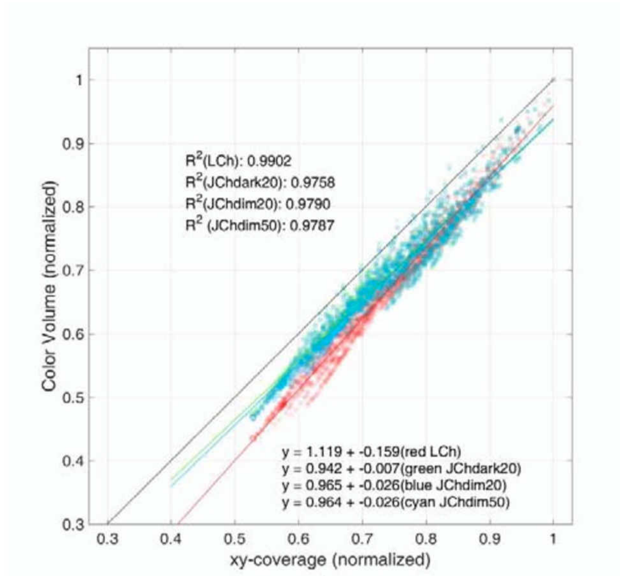
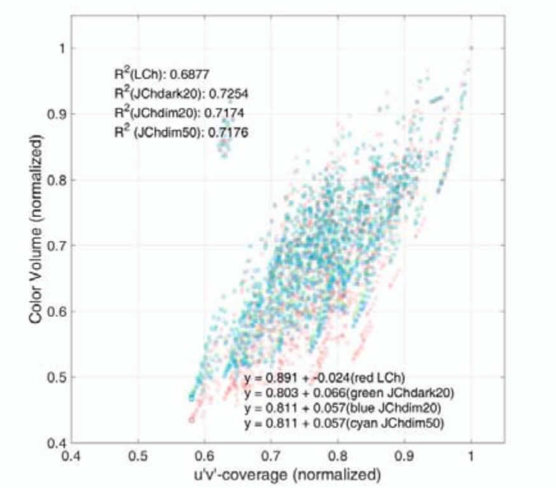


Figure 8. Normalized color gamut volume as a function of normalize chromaticity area (xy) for four different appearance models. Each is linear with a high degree of correlation.

Figure 8 shows the color gamut volumes (normalized for comparison) in each of the four color spaces (CIELAB and CIECAM02 with different parameters) as a function of CIE *xy* chromaticity gamut area. In each case, the linear correlations are quite high (lowest $R^2 = 0.976$) and the fitted lines do a reasonable job of describing the data. Figure 9 shows the same results as a function of CIE *u'v'* chromaticity. Cleary the correlation is not as high, and not useful for predictive modeling. This results is consistent with the previous results.[2,3] These results suggest that, together with the earlier information about CLO/WLO and peak luminance, chromaticity gamut area in CIE *xy* might be used as a proxy for the more difficult computation of color gamut volume in CIELAB or CIECAM02. Thus, a set of simulated displays was



constructed to simultaneously vary all these parameters and test an implementation of a model to predict color gamut volume from simpler measurements.

Figure 9. Normalized color gamut volume as a function of normalized chromaticity area (u'v') for four different appearance models. No meaningful linear correlation exists.

Model and Verification

Three HDR-WCG display properties were varied for creation of independent data to test the predictive model. These were the CIE *xy* chromaticity area coverage (definition of RGB primaries), the peak luminance, and the RGBW CLO/WLO ratio.

The model is as follows:

predVol = xyRatio*peakLumRatio*rgbwRatio*Rec2020Vol (1)

The predicted volume is the product of the chromaticity ratio, peak luminance ratio, RGBW (CLO/WLO) ratio, and the normalizing Rec. 2020 volume as given below. Note that the model parameters are disctinct for CIELAB and CIECAM02 and would be, as expected, for other color spaces.

The constants Rec. 2020 color gamut volume is given in Table 1.

Table 1. Constant Rec. 2020 color gamut volume for examples illustrated in this paper

Diffuse White Type	CIELAB LCh	CIECAM02 JChdim20
Constant 200cd/m^2	3.8586e7	2.5359e7
20% of Peak	0.9578e7	0.7486e7

The RGBW (or CLO/WLO) ratio is computed from the fitted forth-order polynomial as shown in Eq. 2 with parameters from table 2. The rgbw term is the actual CLO/CLO ratio for the display.

rgbwRatio = P1*rgbw^4 + P2*rgbw^3 + P3*rgbw^2 + P4*rgbw^1 + P5 (2)

Table 2. Parameters for computing rgbwRatio in Eq. 2 as a function of CLO/WLO ratio.

Parameter	CIELAB LCh	CIECAM02 JChdim20
P1	-0.509	-0.583
P2	0.655	1.107
P3	-0.715	-1.383
P4	1.580	1.852
P5	-0.011	0.007

The peak luminance ratio is computed using Eq. 3 and parameters in table 3. The peakLum term is the actual peak luminance in cd/m^2. Parameters are given for both constant 200 cd/m^2 diffuse white and for diffuse white set to 20% of peak white.

peakLumRatio = P1*peakLum^2 + P2*peakLum + P3 (3)

Table 3. Parameters for computing peakLumRatio in Eq. 3 as a function of peak luminance.

Parameter	CIELAB LCh (200cd/m^2)	CIECAM02 JChdim20 (200cd/m^2)	CIELAB LCh (20%)	CIECAM02 JChdim20 (20%)
P1	0	-1.55e-8	0	0
P2	2.51e-4	3.00e-4	0	-5.94e-6
P3	-3.40e-4	4.67e-2	1	1.02

Table 4. Parameters for computing rgbwRatio in Eq. 2 as a function of CLO/WLO ratio.

Parameter	CIELAB LCh	CIECAM02 JChdim20
P1	1.119	0.965
P2	-0.1159	-0.026

Finally, the *xy* ratio is computed from CIE *xy* coverage area (xyarea) using Eq. 4 and parameters in Table 4. Rec2020area is equal to 0.2119.

xyRatio = P1*(xyarea/Rec2020area) + P2 (4)

To validate the model 200 random RGB primary sets were selected as illustrated in Figure 10. In addition, peak luminance was randomized in the range from 500 to 4000 cd/m^2. Lastly the CLO/WLO ratios were set to six different values, 0.1, 0.3, 0.5, 0.7, 0.9, and 1.0 (normal RGB). Thus, a total of 1200 simulated HDR-WCG displays were analyzed to compute actual color gamut volume and compare that with the color gamut volume estimated from CIE *xy* chromaticity gamut area, peak luminance, and CLO/WLO ratio.

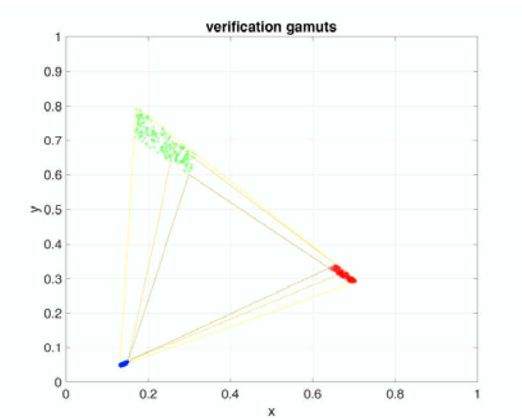


Figure 10. Primary chromaticities, along with Rec. 709, Rec. 2020, and DCI-P3 gamut boundaries, used to create virtual displays for independent verification of the fitted models.

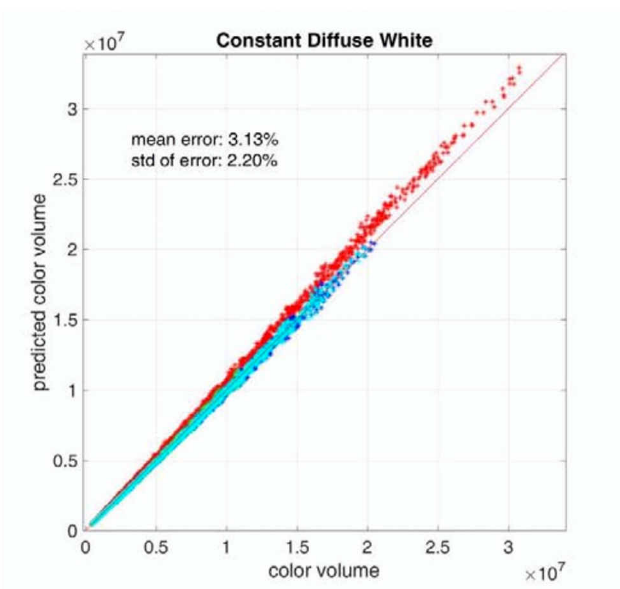


Figure 11. Predicted color gamut volume (from model) as a function of actual computed color gamut volume for appearance calculations with a constant, 200 cd/m^2 diffuse white.

Figures 11 and 12 show the prediction accuracy for displays with a constant diffuse white of 200 cd/m^2 and for displays with a diffuse white of 20% of the peak luminance respectively. Each plot shows the predicted color gamut volume as a function of the computed (i.e. measured) color gamut volume for each of four color spaces. The CIELAB, CIECAM02 JCh (three settings) are the ones examined in this paper. The others simply illustrate that the model works for other setting of CIECAM parameters. In all cases, the predictions are good, but they are significantly better for CIECAM02. The CIELAB predictions seem to be systematically high, especially for larger gamut volumes, which suggests some model improvement might be possible. The overall mean percent error is about 3% for the constant white and about 2.6% for the 20% white. Standard deviations of percent error are of similar magnitude. This is roughly on the order of combined measurement and computation uncertainty for deriving color gamut volumes, which suggest that the described abridged method might be of practical utility.

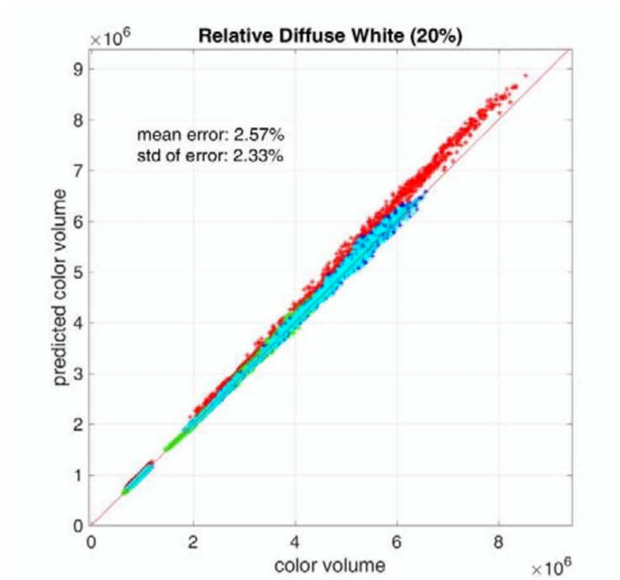


Figure 12. Predicted color gamut volume (from model) as a function of actual computed color gamut volume for appearance calculations with diffuse white equal to 20% of peak white.

Conclusion

It is well established that 3D color gamut volumes, rather than 2D chromaticity gamut areas, are required for meaningful comparison of display color reproduction properties [8, 10]. With the advent and commercial popularity of high-dynamic-range (HDR) and wide-color-gamut displays the examination of color gamut volumes in appropriate color appearance spaces is even more important [1, 8]. However, it is difficult and time consuming to accurately measure color gamut boundaries and also subject to computational approximation in estimating continuous 3D functions with discrete volume areas. This paper examined that problem by algorithmically simulating displays with ideal behavior and then analyzing the various parameters of the displays (e.g. peak luminance, CLO/WLO ratio, etc.) in relation to computed color gamut volumes. The results allowed derivation of a relatively simple empirical model to relate color gamut volume (to typically better than 3% error) to measured peak luminance, CLO/WLO ratio, and CIE *xy* chromaticity gamut area. Thus, color gamut volume can be reasonably estimated from CIE *Yxy* measurements of the RGB primaries and peak white. This procedure could allow the display industry to report more meaningful data (color appearance gamut volume) based on a small number of relatively simple measurements.

It should be noted, that the model parameters described in this paper only apply to the color spaces and settings described. Any future standard technique would require all those decisions to be made (e.g. CIELAB vs. CIECAM02, 20% white vs. 200 cd/m2 white, etc.) prior to a re-derivation of the model parameters. This paper simply shows that the technique works; it does not propose a standard. Moreover, this model is only valid for RGB/RGBW system now. It would need a verification if used for multi-primary system.

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Author Biographies

Fu Jiang is a second-year PhD candidate in Program of Color Science, Rochester Institute of Technology (RIT). Fu Jiang has been working on multi-channel camera analysis tool development, reaction time for different combinations between background color and front color, HDR WCG display appearance. Previously, Fu Jiang received MSc in imaging science from RIT (2016) and BS in physics from Nanjing University of Info Sci & Tech (2013).

Mark Fairchild is Professor and Founding Head of the Integrated Sciences Academy in RIT's College of Science and Director of the Program of Color Science and Munsell Color Science Laboratory. Mark was presented with the 1995 Bartleson Award by the Colour Group (Great Britain) and the 2002 Macbeth Award by the Inter-Society Color Council for his works in color appearance and color science. He is a Fellow of the Society for Imaging Science and Technology (IS&T) and the Optical Society of America. Mark was presented with the Davies Medal by the Royal Photographic Society for contributions to photography. He received the 2008 IS&T Raymond C. Bowman award for excellence in education.

Kenichiro Masaoka is a Principal Research Engineer at NHK Science and Technology Research Laboratories, Tokyo, Japan. He received his Ph.D. in Engineering from the Tokyo Institute of Technology in 2009. He worked with Professors Mark Fairchild and Roy Berns for a six-month residency as a Visiting Scientist at the Munsell Color Science Laboratory at the Rochester Institute of Technology (RIT) in 2012. His research interests include color science and digital imaging systems. In 2017, he received SID's Special Recognition Award for his leading contributions to the research and development of a wide-color-gamut UHD-TV display system and gamut-area metrology.